Dissipation of Oxygen from Outward Leak of Closed-Circuit Breathing Device

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ABSTRACT

Closed-circuit breathing devices recycle exhaled air after scrubbing carbon dioxide and adding make-up oxygen from a tank of pure oxygen. Use of this equipment allows first responders to work for up to four hours without swapping out cylinders. Firefighting situations in which these devices would be useful include tunnels, mines, ships, high-rise buildings, and environments contaminated with biological or chemical toxins. A risk perceived by firefighters entering environments containing open flame and high radiant heat is the possibility of fire ignition in the vicinity of the respirator caused by the outward leakage of oxygen around the facepiece.

This paper presents the progress on a computational fluid dynamics (CFD) study of oxygen dissipation into the environment surrounding a respirator facepiece. Actual heads and masks have been scanned into a 3D data set for entry into the CFD software, providing a physical boundary for the problem to be solved. Leak geometries representing an imperfect seal are defined. Oxygen concentration fields and flow streamlines will be determined for multiple leak geometries and for both normal and high stress breathing patterns.

INTRODUCTION

The National Institute for Occupational Safety and Health (NIOSH) is developing standards for the use of closed-circuit self-contained breathing apparatus (SCBA) by firefighters and other first responders after a terrorist attack (NIOSH/NPPTL 2004, NIOSH 2005). In addition to the respiratory protection of first responders against chemical, biological, radiological, and nuclear (CBRN) agents, the equipment must be usable under conditions of high heat and open flames. Although a leak is unlikely for a respirator with good fit, the possibility of outward leakage of oxygen in a fire environment is a concern. If the oxygen remains concentrated around the face in the presence of fuel gases and heat, ignition may occur. If the oxygen diffuses rapidly away from the face, however, the possibility of ignition is negligible.

Computational fluid dynamics (CFD) numerically simulates fluid flow by solving the equations of motion. The solutions can be obtained in detail that is impossible to achieve in experiments, and for variables that may not be practically achievable, especially in three-dimensional space. The visualization of the computational results as they vary with time and space enhances our understanding of the flow phenomena. However, validation of CFD with experimental measurements is necessary to ensure that the results accurately reflect reality. For the work presented here, a commercial CFD software package called CFD-ACE+ is used.[1]

Experiments using mannequins have demonstrated that a simplified cylindrical geometry is not adequate to represent the flow field near a human face (Anthony et al., 2005). The complex features of the human face combined with the features of a respirator mask are necessary for an accurate flow model.

MODEL GEOMETRY

For this modeling effort, the complex geometry for a human head wearing a respirator facepiece has been obtained by assembling the shapes for a head and a facepiece that were developed separately. A three-dimensional scan of a headform used by NIOSH in respirator breathing experiments provided a set of data points that defined the location of its surface. For a prototypical respirator facepiece, mechanical drawings from the manufacturer enabled a geometry to be built from the relative locations of points, curves, and surfaces. Figure 1 shows the facepiece and headform after processing, as they appear in the commercial CFD software.

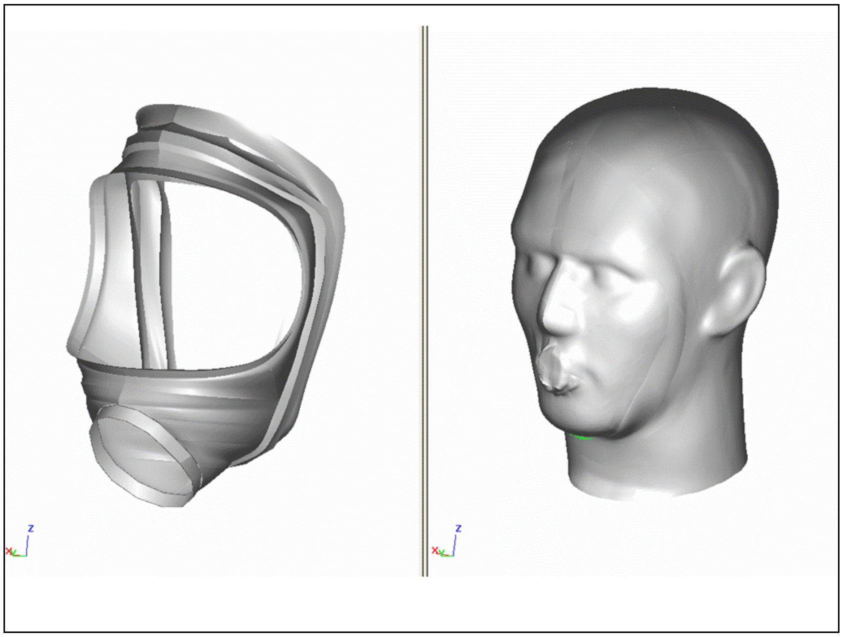

Figure 1. Geometries for prototypical respirator facepiece (left) and NIOSH experimental headform (right).

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[1] Certain trade names and company products are mentioned in the text in order to specify adequately the equipment used. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.

To combine the head with the facepiece, the head was translated and rotated into the proper position relative to the mask. A simple merge of the two geometries did not provide a good fit; with the chin in good position, the top of the facepiece was not in contact with the forehead, and the sides actually extended inside of the headform by more than a centimeter. This discrepancy is eliminated in the real world by the flexibility of the facepiece, which allows it to fit the shape of the head as it is put on. A good fit was achieved in the virtual world through adjustment of the facepiece geometry by moving the top toward the forehead, pulling out the sides, and defining the inner and outer seals to follow the contours of the face. The result is shown in Figure 2.

Figure 2. Model geometry for headform combined with respirator facepiece. Red mark indicates a possible location for a leak.

In this study, the geometry for a leak is defined by the modeler. A representative leak location is shown in Figure 2 as a thin red line in front of the ears. This leak is along the outer seal of the facepiece. Leaks ranging from the dimensions of a pinhole to a thin breach of the outer seal extending around its entire length will be considered.

CFD MODELING

Given the symmetry in this model, the size of the computational problem that must be solved can be cut in half. This was taken into account during generation of the symmetrical respirator facepiece from the mechanical drawings, which required only half of the geometry. For the headform, the geometry was split in half along the centerline to take advantage of symmetry. Figure 3 shows a geometry for investigating the flow field and oxygen concentration external to the head-facepiece combination. A box is drawn to encompass the head plus a sufficient volume of the surroundings such that the locations of the walls of the box have negligible effect on the results in the immediate vicinity of the leak. A sensitivity study will be performed to ensure that this is indeed the case.

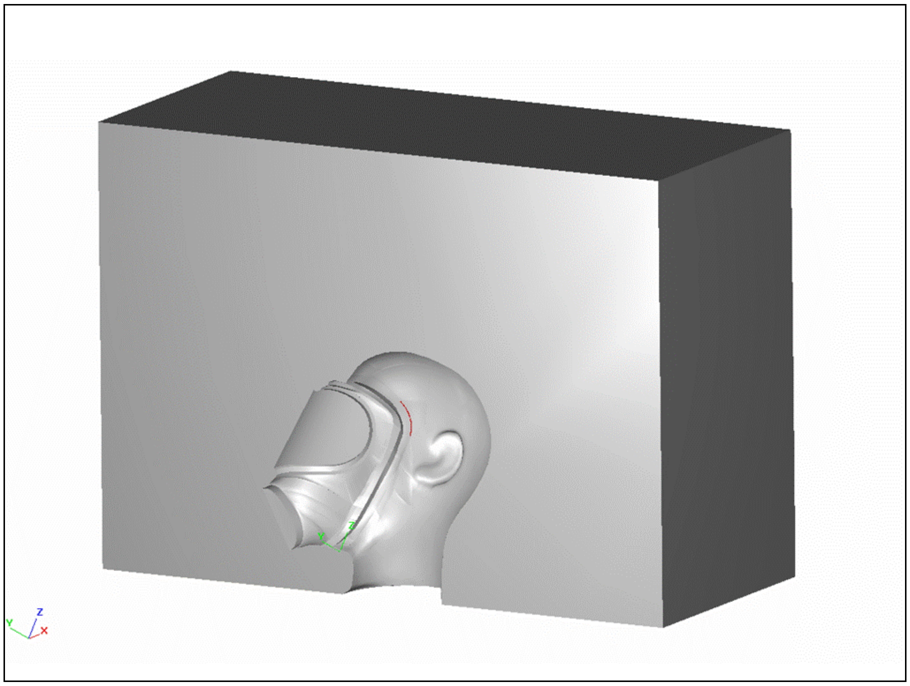

Figure 3. Model geometry for solving flow in the environment external to facepiece.

The region enclosed by the exterior surfaces of head and facepiece plus the walls of the box will be divided into a tetrahedral finite element mesh to be used for computing the solution. The CFD-ACE+ software for mesh generation automatically concentrates the mesh in the area around the thin leak, with much larger elements near the walls where fine detail is not necessary.

To fully define the model, boundary conditions must be applied to all surfaces. The boundary conditions for the leak are most critical. At the leak oxygen flows out with an assigned velocity profile as a function of time. Cases will be run for flow rates that correspond to both normal breathing and to breathing under high stress. Except for the leak, the head and facepiece are assigned no-slip conditions, for which velocity is set to zero. The velocities at the walls of the box are expected to be low, though not zero. Velocities on these boundaries may be restricted to the perpendicular direction. The worst case for oxygen buildup will be still air, so this will be assumed for the initial conditions. Initially, the computational space is filled with fuel gases.

The problem is completed by including the material properties of the fuel gases, which will be treated as a single fluid, and oxygen. The important variable is the concentration of oxygen as it leaks into the surrounding environment. Visualization tools will be used to observe the flow field and oxygen concentration as functions of space and time.

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